

Coronal Gamma Ray Bursts as the sources of Ultra High Energy Cosmic Rays?

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ABSTRACT

I consider the possibility that Ultra High Energy Cosmic Rays are accelerated in Gamma Ray Bursts located in the Galactic corona, thus circumventing the problem raised by Greisen–Zatsepin–Kuz'min cutoff. The acceleration of UHECRs could occur in the pulsars which, in the coronal GRB model, produce them: the same parameters that permit fitting GRBs' observations in the model of Podsiadlowski, Rees and Ruderman (1995) lead to an estimate of the highest achievable energies corresponding to that of the Bird *et al.* (1994) event, and to very low luminosities in cosmic rays. I show that, if the observations of Milgrom and Usov (1995a) are confirmed, the extragalactic GRBs' model for the acceleration of UHECRs is untenable, but the same constraint does not apply to the coronal model. Also, I show that the efficiency of particle acceleration needs be much smaller (and less demanding) than in cosmological models of GRBs. Uncertainties remain about the ensuing cosmic ray spectral distribution. I also briefly discuss observational strategies to distinguish between the two possibilities.

Key words: acceleration of particles – stars: neutron – gamma-rays: bursts

1 INTRODUCTION

The recent discovery of the two highest energy CRs ever (Bird *et al.*, 1994, Yoshida *et al.*, 1995) has produced a renewal of interest in the acceleration of Ultra High Energy Cosmic Rays (UHECRs). This is due to the well-known Greisen–Zatsepin–Kuz'min effect: because of photo-pion losses, a proton with $E = 10^{21}$ eV at the source needs only cross a distance ≈ 30 Mpc (Protheroe and Johnson 1995) to be slowed down to $E = 3 \times 10^{20}$ eV. Thus it is necessary to identify acceleration sites which are reasonably close to the Earth.

It has been recently pointed out (Milgrom and Usov 1995a, Waxman 1995a, Vietri 1995) that UHECRs may be accelerated in cosmological Gamma Ray Bursts, GRBs. It was shown (Vietri 1995) that CRs' energies as high as the largest ever observed ($E \approx 3 \times 10^{20}$ eV, Bird *et al.*, 1994) can be achieved in the very short durations (≈ 1 sec) of GRBs by means of very efficient first-order Fermi–Bell acceleration in just *two* cycles. However, as it is well-known (Lamb 1995, Paczyński 1995), the nature and location of GRBs is in dispute, the most likely alternative to the extragalactic model being a distribution of neutron stars in an extended Galactic corona, at Galactocentric distances ≈ 100 kpc, and it may be interesting to consider whether UHECRs can be accelerated in coronal GRBs.

This idea seems to subvert the traditional view (Cocconi 1956) that UHECRs are of extragalactic origin, the main evidence for this lying in the change of chemical composition and spectral slope at the 'ankle' ($E = 3 \times 10^{18}$ eV). However, the objects postulated to give rise to coronal GRBs form a unique population, not just because their flux and angular distributions are sharply at odds with those of all known Galactic populations and identical to those of all known extragalactic sources, but also because their Galactocentric distances exceed by an order of magnitude those of known Galactic objects. Thus, the hiatus that separates Galactic and extragalactic UHECRs' sources exists in this model as well. The classical way to try to establish the extragalactic nature of the sources giving rise to UHECRs has been to seek the GZK–cutoff in the CRs' flux observed at the Earth. At present, however, the evidence is lacking statistical significance (Sigl *et al.*, 1995), and does not rule out the coronal model.

It seems thus worthwhile to consider whether UHECRs can be originated in these nearer models for GRBs. I shall point out below three reasons why this seems attractive. A discussion will follow in Section 5.

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2 THE ACCELERATION OF UHECRS IN CORONAL GRBS

The essential feature of the extragalactic GRB model that is preserved by the Coronal model is that GRBs are located inside the Greisen–Zatsepin–Kuz'min (GZK from now on) sphere. The traditional acceleration sites for UHECRs, Fanaroff–Riley Class II radio galaxies (Rachen and Biermann 1993) certainly provide an energetically attractive source of UHECRs, despite the large uncertainties in the estimates of the proton flux at the source. However, the nearest such galaxy, Pictoris A, lies at $d_{PA} = 100 \text{ Mpc}$. The GZK-radius for $E \gtrsim 2 \times 10^{20} \text{ eV}$ is $R_{GZK} = 20 \text{ Mpc}$ (Protheroe and Johnson 1995), so that the total flux emitted by Pictoris A is damped by the factor $\exp(d_{PA}/R_{GZK}) \approx 100$. It will be shown later that 1 extragalactic GRB is expected within a GZK-sphere every 10^3 years. If this emits equal amounts of energy in γ -ray photons and CRs (not just UHECRs), then the expected ratio of fluxes at the Earth is

$$\frac{f_{GRB}}{f_{PicA}} \approx 0.1 \exp(d_{PA}/R_{GZK}) \approx 10. \quad (1)$$

The super-GZK flux by FR II galaxies is even more strongly dominated by coronal GRBs: all coronal GRBs are located inside R_{GZK} , as opposed to just a fraction $(R_{GZK}H_0/c)^3 \approx 10^{-6}$, giving a flux of super-GZK CRs higher by a factor $c/H_0 R_{GZK} \approx 10^2$. Also, coronal GRBs, exactly like their extragalactic counterparts, are largely super-Eddington, and hyperrelativistic phenomena like beaming naturally arise around them, thus mirroring the discussion in Vietri (1995) that made GRBs attractive as potential sources of UHECRs.

The mechanism for the acceleration of UHECRs in cosmological GRBs (Vietri 1995) surely does not work for the coronal model, because the model of an extragalactic GRB as due to the prompt release of a shock's whole energy immediately after formation, by self-synchro-Compton of relativistic electrons (Mészáros and Rees 1994) requires high ISM densities to achieve sufficient efficiencies, $n \approx 1 \text{ cm}^{-3}$ (see also Begelman, Mészáros, Rees 1993). Such high baryonic densities are inconceivable at the distances ($\approx 100 \text{ kpc}$, Podsiadlowski, Rees and Ruderman 1995, PRR from now on) currently postulated for the coronal scenario, where the dark matter density is $\rho_{dm} \approx 3 \times 10^{-3} m_H \text{ cm}^{-3}$, and thus most likely $n \lesssim 10^{-4} \text{ cm}^{-3}$. Models for coronal GRBs cannot simply be those concocted when GRBs were thought to lie at $\approx 1 \text{ kpc}$ from us, because the greater distance scale implies release of $\approx 10^4$ times more energy. Recently, however, PRR have shown that a reasonable GRB-generation mechanism can be identified in the stress-release episodes of the crustal magnetic field, provided $B \approx 10^{15} \text{ G}$. This suggests that cosmic rays may be accelerated in pulsars' magnetospheres. Sigl, Schramm and Bhattacharjee (1994) give as the highest cosmic ray energy from a pulsar

$$E_{max} = 2 \times 10^{20} \text{ eV} \left(\frac{B}{10^{15} \text{ G}} \right). \quad (2)$$

The above formula was discussed in this context also by Milgrom and Usov (1995a); the novel point is the 'coincidence' that the same magnetic field is necessary to explain both the GRB and the UHECR phenomena. While no more specific predictions can be made because of the lack of a detailed coronal GRB model, I find this coincidence encouraging.

3 COINCIDENCES BETWEEN UHECRS AND GRBS

Another reason why the coronal gamma-ray-burst hypothesis is attractive comes about when we consider the implications of the work by Milgrom and Usov (1995a). They discovered that the two super-GZK events (Bird *et al.* 1994, Yoshida *et al.*, 1995) were positionally coincident, within their largish error boxes, with two strong GRBs which preceded them by $\lesssim 1 \text{ yr}$; on the basis on this association they proposed that UHECRs are generated in GRBs. If one believes in this association, the following argument shows that GRBs are unlikely to be extragalactic. Let us compute the expected rate of GRBs resulting in super-GZK events at the Earth. Given that the rate of GRBs is (Paczynski, 1993) $\dot{n} = 30 \text{ Gpc}^{-3} \text{ yr}^{-1}$, and that a Greisen–Zatsepin–Kuz'min sphere with radius $R_{GZK} = 20 \text{ Mpc}$, for $E = 2 - 3 \times 10^{20} \text{ eV}$, (Protheroe and Johnson 1995) has volume $V_{GZK} = 3 \times 10^4 \text{ Mpc}^3$, I find that a GZK-sphere has a rate of 1 GRB every 10^3 yr . However, in the $\approx 10 \text{ yr}$ of combined observational time of the Fly's Eye and AGASA experiments, two such events have been already observed. This occurs, in the above model, with probability $P_2 = (10q/10^3)^2 \approx 10^{-5}$, where q is the averaged fraction of sky coverage, which has been taken as $q \lesssim 0.3$. Stated another way, for these low values of R_{GZK} and of the time-delay, most of the time (always but just once in 10^3 yr) we should not be able to observe any super-GZK CR. It follows that, if the proposed observational connection and time delay ($\lesssim 1 \text{ yr}$) were to be confirmed, the sources that produce UHECRs could not be extragalactic GRBs.

The above observation is of course unlikely even when viewed from the other angle, that of GRBs. Milgrom and Usov (1995a) had at their disposal $\approx 3 \text{ yr}$ of the BATSE catalog. This implies then that the probability of seeing 2 GRBs located within R_{GZK} is also given by $(3/10^3)^2 = 10^{-5}$, fortuitously equal to P_2 above. Another way to look at the same problem is to compute the total energy released by the two GRBs that Milgrom and Usov (1995a) associated with the two highest energy CRs. They have fluences of $4 \times 10^{-5} \text{ erg cm}^{-2}$ and $3 \times 10^{-4} \text{ erg cm}^{-2}$, which assuming a distance $= R_{GZK} = 20 \text{ Mpc}$, correspond to a total energy release of $10^{48} - 10^{49} \text{ erg}$. This is low when compared with the average energy released by GRBs, $4 \times 10^{51} \text{ erg}$ (Piran 1992). While it is certainly possible that the GRBs' luminosity function is broad, still the smallness of the total energy released computed thusly is in keeping with the argument developed above.

It should be noticed that the previous argument is based upon the smallness of $R_{GZK} = 20 \text{ Mpc}$. Protheroe and Johnson (1995) compare their results with several previous computations, and it is apparent from their Fig. 4 that theirs is the largest value in the energy range of interest here, some authors having obtained values as low as $R_{GZK} = 9 \text{ Mpc}$.

Independently of the actual time-delay, it seems very unlikely to me that any GRB in the BATSE catalog can come from within the GZK-sphere. One way out of this predicament is, of course, if the time-delay is actually much longer than proposed by Milgrom and Usov (1995a); in this case there need be no GRB from inside the GZK sphere in the BATSE catalog, and, if it is assumed that CRs from the same source are spread out over a time comparable to the

time-delay, then perhaps a hundred distinct extragalactic GRBs as sources of UHECRs should be seen at all times (see later on). More data should settle this issue. In the following I shall assume the connection and the time-delay ≈ 1 yr to be correct. In this case the above predicament would be relieved if coronal GRBs were to produce super-GZK CRs, first because photopion and photoelectron losses within the Galaxy are entirely negligible (and thus several GRBs from within the UHECR error box can be the putative fathers of the super-GZK events), and second because there is no need that the objects giving rise to GRBs produce UHECRs only during fireballs: they could instead produce a steady flux of CRs. Under the coronal hypothesis, the time-delays of ≈ 1 yr can easily be accommodated (Milgrom and Usov 1995a).

4 THE EFFICIENCY

Another reason why a Coronal GRB origin for UHECRs is attractive is due to the fact that it was quickly realized (Vietri 1995, Waxman 1995a, Milgrom and Usov 1995b) that accounting for all UHECRs observed at Earth requires that each extragalactic GRB releases approximately equal amounts of energy in γ -ray photons and in UHECRs, *i.e.*, very high efficiency. In order to see how serious this efficiency problem is, it is convenient to compare the expected production by GRBs of UHECRs in the range $10^{19} \text{ eV} < E < 10^{20} \text{ eV}$ with that deduced from observations (Waxman 1995b), $\epsilon_{obs} = 5 \times 10^{-37} \text{ erg s}^{-1} \text{ cm}^{-3}$. The observed rate of GRBs is $\dot{n} = 30 \text{ Gpc}^{-3} \text{ yr}^{-1}$ (Paczynski, 1993). The average GRB total energy output in photons E_γ is $4 \times 10^{51} \text{ erg}$ (Piran 1992). This yields the total energy release rate in γ -ray photons. To estimate the release rate of energy in UHECRs I proceed as follows. The fraction q of the directed kinetic energy that shocks convert into CRs, compared to that converted into thermal motions (which in GRBs is promptly dissipated into γ -ray photons) is very uncertain, and is variously estimated (Draine and McKee 1993) between 0.03 and 0.5. I shall take the larger value. The spectrum emitted by a cosmological source is derived from observations (Waxman 1995b) as $\propto E^{-2.3}$. I shall consider a harder spectrum, $\propto E^{-2}$, so as to continue to overestimate the production of UHECRs by GRBs. Then the total fraction of energy released in cosmic rays, and channeled in the range discussed by Waxman, $10^{19} \text{ eV} < E < 10^{20} \text{ eV}$, is $p = \ln 10 / \ln(E_{max}/E_{min})$. I shall conservatively take $E_{max} = 10^{20} \text{ eV}$, and $E_{min} = 10^{15} \text{ eV}$. This last value comes from this argument. Vietri (1995) took as would-be CRs the extreme Boltzmann tail of the just-shocked ISM protons, for which $\gamma \approx 10^2 - 10^3$ in the shell frame. In the lab frame these protons would appear as CRs with $E \approx 10^{13} - 10^{15} \text{ eV}$, corresponding to the range in γ . Together, these two factors imply a relative efficiency of UHECRs to γ -ray photons of $\eta = E_{UHECR}/E_\gamma = qp \approx 1/10$. The comparison with observations yields

$$\frac{\epsilon_{GRB}}{\epsilon_{obs}} = \frac{\dot{n} E_\gamma \eta}{\epsilon_{obs}} = 0.03, \quad (4)$$

despite my attempts at maximizing the contribution of GRBs. Thus it seems likely that, in order to reproduce observations, GRBs must overproduce UHECRs with respect

to conventional models, by a factor $10 - 100$, *i.e.*, $\eta \approx 1 - 10$. It should be emphasized that large efficiencies are not impossible: the above estimate is very uncertain, and it refers to steady-state, newtonian shocks because no analogous computations are known to me in the time-dependent, relativistic regime. However, in the face of the daunting task of raising the efficiency by about two orders of magnitude, it seems worthwhile to consider the alternative hypothesis that GRBs originate in the Galactic corona.

The efficiency requirement becomes immediately less stringent in the coronal model. In fact, if UHECRs are generated by cosmological GRBs, only those originating within R_{GZK} , the Greisen-Zatsepin-Kuz'min radius, of the Milky Way can reach us. This is because UHECRs with $E \gtrsim$ a few times 10^{19} eV lose energy by photopion and photoelectron production off CMBR photons. These nearby GRBs account for a fraction $f \approx R_{GZK}/(c/H_0)$ of the whole flux at Earth. On the other hand, if GRBs are located in the Galactic Corona, all GRBs generate UHECRs that reach the Earth. The coronal GRBs' energy release ($E_{GRB} \approx 10^{41} \text{ erg}$) is determined so that the flux of photons at Earth is equal to that in the cosmological model; thus the coronal model with the same efficiency factor η as the extragalactic model produces an UHECRs' flux at Earth higher by the factor $1/f$ with respect to the extragalactic model. With $R_{GZK} = 20 \text{ Mpc}$ (Protheroe and Johnson 1995), for $E \approx 3 \times 10^{20} \text{ eV}$, the overproduction is $1/f \approx 10^2$. This implies that, in the coronal model, the fitting of the observed UHECRs' flux can be achieved with an efficiency η reduced by the factor f to $\eta \approx 0.03$.

5 DISCUSSION

The low efficiency $\eta \approx 0.03$ discussed above is rather rewarding in the case in which UHECRs are generated during GRBs. However, another, more effective way for the low value of f to ease our luminosity quandaries occurs if the UHECR-production is steady, within the PRR model. In fact, PRR postulate that every pulsar remains active for up to 10^{10} yr , producing $\approx 10^6$ stress-release episodes within its lifetime. This means a GRB every 10^4 yr , which equals a time-averaged GRB-luminosity of $\approx 3 \times 10^{29} \text{ erg s}^{-1}$. With $\eta \approx 0.03$, this leads to a continuous UHECR-luminosity of $L_{UHECR} \approx 10^{28} \text{ erg s}^{-1}$.

However, let me remark that, if the release of the UHECRs were coincident with the event leading to the GRB, the acceleration of UHECRs could use as an energy source the very same one of the GRB, and it would be energetically insignificant since $\eta \approx 0.03$. This would also leave room for the acceleration of several other decades of CRs' energy beyond the one considered, $10^{19} \text{ eV} < E < 10^{20} \text{ eV}$, even assuming a softer spectrum. It is more difficult to identify an energy source in the case of continuous acceleration of CRs: with a field $B \approx 10^{15} \text{ G}$, the rotational kinetic energy of the pulsar must have been exhausted very early indeed.

Another observational feature, the dominance of protons with respect to heavier nuclei beyond the ankle ($E = 3 \times 10^{18} \text{ eV}$, Bird *et al.*, 1994, 1995), which is often cited as evidence for the extragalactic origin of UHECRs, can be accommodated easily within this model. Iron nuclei with $E \approx 10^{20} \text{ eV}$ have gyroradii $r_L \approx 5 \text{ kpc}$ in the Galactic

magnetic field, so that they are essentially confined around the pulsars producing them. All diffusion processes tend to push them away from us, and into the IGM, thus making them unobservable to us. Protons of comparable energy have much larger gyroradii (≈ 100 kpc), which allow them to penetrate into the inner Galaxy.

The most significant weakness of the coronal model is that the expected spectrum is not necessarily close to E^{-2} , as it automatically is every time CR acceleration at shocks is invoked. This point is clearly in need of further investigation.

Neglecting the thornier question of establishing a connection between UHECRs and GRBs, I discuss now a comparison between the extragalactic and coronal models for GRBs as sources of UHECRs. As stated earlier, spectral evidence can distinguish between the two models, and, with the arrival of the next generation of detectors, the test is feasible (Sigl *et al.*, 1995). Another significant observational difference between the two models occurs when we consider the angular distribution of super-GZK events. In the coronal model, they must be isotropic because the GRB model (PRR) is designed to fit the observations (Meegan *et al.*, 1992), except for the very small dipole anisotropies predicted, \approx a few times 10^{-2} . In the extragalactic model, super-GZK CRs must occur within a GZK sphere, with $R_{GZK} \lesssim 30$ Mpc. Within this distance the peculiar velocity of the Galaxy is formed (Scaramella, Vettolani and Zamorani 1994), so that we expect larger anisotropies. Here, I cannot help but notice the irony that it is the detection of an isotropy that would favor the local model, the only such case known to me in astronomy.

For sufficiently large detectors, the total number of independent directions of arrival in the coronal model must be at least as large as that of known GRBs, a few thousands. This differs sharply from the number expected for the extragalactic model. From within a sphere $R \lesssim 30$ Mpc (corresponding to the path-length of a CR which started out with $E = 10^{21}$ eV and is observed with $E = 3 \times 10^{20}$ eV) we expect in fact ≈ 1 GRB every 300 years. The most reasonable time-delay over R_{GZK} is given by

$$\Delta t = 3 \times 10^4 \text{ yr} \left(\frac{R}{30 \text{ Mpc}} \right)^3 \left(\frac{B}{1 \text{ nG}} \right)^2 \quad (4)$$

and this, assuming that the UHECRs coming from a GRB are spread over a timescale $\approx \Delta t$, means that ≈ 100 independent sites from which super-GZK CRs are coming, are visible at all times. Thus about an order of magnitude separates the number of different acceleration sites visible in the two models, the coronal one being the more densely populated.

Assuming the validity of the extragalactic model, I would like to point out that the above-determined rate of GRBs inside the GZK-sphere, $\dot{n}_{GZK} = 1/10^3 \text{ yr}$, allows a measurement of the time-delay between GRBs and UHECRs, in a different range than the one ($\approx 1 \text{ yr}$) discussed by Milgrom and Usov (1995a). In fact, suppose that experiments with perfect sky coverage were to reveal the existence of N small regions on the plane of the sky from which super-GZK events seem to arrive. Then, we can use the inverse of the rate above, $1/\dot{n}_{GZK}$, as a universal clock to state that the time delay is $\approx N/\dot{n}_{GZK}$. The areas of the small regions is limited from below by instrumental resolution, or by the deflections of particles along their flight-path to our detec-

tors. Since, from conventional estimates of the magnetic field it is found that deflection angles of a few degrees are most likely for UHECRs (Sigl, Schramm and Bhattacharjee 1994), we expect to be able to resolve at most $\approx 10^3$ such clusters. This means that the time-delay that can be measured is in the range $1/\dot{n}_{GZK} - 10^3/\dot{n}_{GZK}$, i.e., $10^3 - 10^6 \text{ yr}$. A detailed study of this measurement will be presented elsewhere.

In summary, the model of PRR, designed to fit the observations of GRBs, also naturally accounts for the energy of the super-GZK CRs observed so far. The same model also avoids the efficiency problem of the extragalactic competitor, and is consistent with the statistical significance of the coincidences found by Milgrom and Usov (1995a). Angular distribution properties are sufficiently distinct from those of the extragalactic model to make discrimination of the two models feasible with the next generation of detectors.

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